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Sound propagation through anisotropic, inhomogeneous and intermittent turbulence

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13. ABSTRACT (Maximum 200 words)

Three-dimensional models of anisotropic and inhomogeneous spectra of temperature and wind velocity fluctuations in unstable atmospheric boundary layers have been developed, modified or extended. Furthermore, theories of sound propagation through anisotropic, inhomogeneous, and intermittent atmospheric turbulence have been developed. These theories allow consideration of different geometries of sound propagation: line-of-sight sound propagation, interference of the direct and ground reflected waves, sound scattering into a refractive shadow zone, and waveguide sound propagation. Using the spectra developed or adopted from the literature, it was shown that anisotropy, inhomogeneity, and intermittency of atmospheric turbulence can significantly affect the statistical moments of a sound field for these geometries. Some of the theoretical results obtained have been verified experimentally.

Two related tasks have also been accomplished. First, a new scheme of source localization in the atmosphere by means of acoustic tomography was proposed. The scheme accounts for sound refraction in the atmosphere and allows retrieval of vertical profiles of temperature and wind velocity. Secondly, it was shown that, in many cases, the effects of sound refraction on acoustic remote sensing of wind velocity and the structure parameters of temperature and velocity fluctuations are significant. Algorithms were developed to account for these effects in acoustic remote sensing of the atmosphere.

14. SUBJECT TERMS
3D models of anisotropic and inhomogeneous atmospheric turbulence. Theories of sound propagation: line-of-sight sound propagation, interference of the direct and ground reflected waves, sound scattering into a refractive shadow zone, waveguide sound propagation. Source localization in the atmosphere by means of tomography.

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1 STATEMENT OF THE PROBLEM STUDIED

The main goal of the grant was development of three-dimensional (3D) models of anisotropic, inhomogeneous, and intermittent atmospheric turbulence in unstable (daytime) atmospheric boundary layers (ABL) and studies of sound propagation through such turbulence. This goal is important for improvement of performance of U.S. Army "smart" weapons and acoustic sensors intended for source detection. Furthermore, it is important in other fields such as boundary layer meteorology, electromagnetic and acoustic wave propagation in a turbulent atmosphere, acoustic remote sensing of the atmosphere, etc.

Specific tasks of the grant and their accomplishment are presented below in section 2. Note that the tasks 1 – 5 are original tasks of the grant. When accomplishing these tasks, we obtained results that had broader range of applicability. Therefore, it was worthwhile to consider two additional tasks 6 and 7. These additional tasks are important for improvement of performance of smart weapons and acoustic sensors, and for acoustic remote sensing of the atmosphere by sodars which is used by the Army Research Laboratory (ARL).

2 SUMMARY OF THE MOST IMPORTANT RESULTS

We have developed, modified and extended 3D models of anisotropic and inhomogeneous spectra of temperature and wind velocity fluctuations in unstable ABL. Furthermore, we have developed theories of sound propagation through anisotropic, inhomogeneous and intermittent atmospheric turbulence. In these theories, we considered several geometries: line-of-sight sound propagation, interference of the direct and ground reflected waves, sound scattering into a refractive shadow zone, and waveguide sound propagation. Using the obtained 3D spectra of atmospheric turbulence, we have showed that anisotropy, inhomogeneity, and intermittency of turbulence can significantly affect the statistical moments of a sound field in these geometries. Some of the theoretical results obtained have been verified experimentally. Furthermore, a new scheme of source localization in the atmosphere by means of acoustic tomography was proposed and the effects of sound refraction on acoustic remote sensing of the atmosphere by sodars were studied.

The accomplishment of the grant was done in a close collaboration with Dr. K. Wilson and Dr. H. Auvermann of the ARL. They are coauthors in 20 of the total of 28 papers devoted to accomplishment of the grant. This means direct transfer of the results obtained for needs of the ARL.

Specific tasks of the grant and their accomplishment:

Task 1 To modify and extend existing 3D models of anisotropic, inhomogeneous, and intermittent atmospheric turbulence in unstable ABL for use in developing theories of sound propagation and scattering in a turbulent atmosphere.

Accomplishment:

This task was completed in references [7,16,25,28], see the list of publications. First, a 3D model of inhomogeneous, isotropic turbulence was developed in references [7,16]. In this model, 3D spectra of temperature and velocity fluctuations are approximated by von Karman spectra. In these spectra, the variances and the outer scales of temperature and velocity fluctuations realistically depend on the height above the ground for shear and buoyancy produced turbulence. Secondly, a quasi-wavelet model of anisotropic, inhomogeneous turbulence was developed [25]. Third, the intermittency of atmospheric turbulence was modeled by al-

lowing the structure parameters of temperature fluctuations C_T^2 and velocity fluctuations C_v^2 be random functions along the sound propagation path with log-normal probability density functions [28]. Fourth, Mann's spectrum [J. Fluid Mech. **273**, 141-168 (1994)] of shear driven anisotropic inhomogeneous turbulence was adopted for studies of sound propagation.

Task 2 To generalize the modern theory of line-of-sight sound propagation through isotropic and homogeneous turbulence, which has been developed towards accomplishment of our previous ARO project (1995-1998), to the case of sound propagation through anisotropic, inhomogeneous and intermittent turbulence.

Accomplishment:

This task was completed in references [10,17,24,26,28], where a theory of line-of-sight sound propagation through anisotropic, inhomogeneous, and intermittent atmospheric turbulence with temperature and velocity fluctuations was developed. In this theory, analytical formulas for the variances and correlation functions of log-amplitude and phase fluctuations, the mean sound field and the coherence function of the sound field were derived. Using these formulas and Mann's spectrum of shear driven turbulence, it was shown that turbulence anisotropy and inhomogeneity can dramatically affect the statistical moments of a sound field. For example, figure 1 from reference [26] shows the normalized variances of log-amplitude fluctuations of a plane sound wave versus the diffraction parameter which is proportional to the distance x of sound propagation in a turbulent atmosphere. The solid and dashed lines correspond to along wind and crosswind sound propagation. (The dotted line corresponds to an isotropic von Karman model.) It follows from the figure that the variances of log-amplitude fluctuations significantly depend on a direction of sound propagation. Also, it was shown that the intermittency of atmospheric turbulence results in increases in the mean sound field and the coherence function [28].

Task 3 To develop a theory of the interference of the direct wave from source to receiver and that reflected from the ground in a presence of anisotropic, inhomogeneous and intermittent turbulence.

Accomplishment:

This task was completed in references [3,4,11,23]. Two theoretical approaches for calculating the interference of the direct and ground reflected waves in a turbulent atmosphere were developed. The first approach employs the spectral representation of refractive-index fluctuations [3]. In the second approach, a formula for the mean squared sound pressure $\langle|p|^2\rangle$ was derived using a parabolic equation method [4,11,23]. The effects of turbulence anisotropy on $\langle|p|^2\rangle$ were studied numerically [4].

Task 4 To develop a theory of sound scattering into a refractive shadow zone in an atmosphere with anisotropic, inhomogeneous and intermittent temperature and wind velocity fluctuations.

Accomplishment:

This task was completed in references [5,6,8,13,18,20,22]. First, a theory of sound scattering into a refractive shadow zone in an atmosphere with anisotropic, inhomogeneous, and intermittent turbulence was developed in [5,13,18]. In this theory, closed equations for the statistical moments of arbitrary order of the sound-pressure field were derived for anisotropic and inhomogeneous spectra of temperature and velocity fluctuations. The intermittency of turbulence can be accounted for by allowing C_T^2 and C_v^2 be random functions in these equa-

tions. Numerical algorithms for solving the equations obtained were developed. Figure 2 shows the second moment of the sound pressure (relative to spherical spreading) calculated with the use of these algorithms and inhomogeneous von Karman spectrum of velocity fluctuations. In figure, the shadow zone starts at about 600 m from the source. Without atmospheric turbulence, the sound pressure in the shadow zone would be by 10 – 15 dB less than that in figure 2. Note that the theory developed in [5,13,18] also allows calculation of the statistical moments of a sound field for the case of waveguide sound propagation. Secondly, in references [6,20], a theory and a computer algorithm were developed to predict time dependence and frequency spectra of sound scattered by atmospheric turbulence flowing with a horizontal wind. Third, in references [8,22], a formula for the sound scattering cross section in an atmosphere with arbitrary profiles of temperature and wind velocity was derived. This formula is important because the mean squared sound pressure scattered into a refractive shadow zone can be expressed in terms of the sound scattering cross section.

Task 5 To compare theoretical results obtained with experimental data.
Accomplishment:
A comparison between results obtained and experimental data was done in references [4,6,14,19,20]. First, in references [4,14,19], theoretical predictions of the mean squared sound pressure $\langle |p|^2 \rangle$ obtained in task 3 were compared with experimental data measured in a laboratory experiment in a large anechoic chamber at Ecole Centrale de Lyon, France. The comparison showed a good agreement between theory and experiment. Secondly, in references [6,20], a frequency spectrum of sound scattered by atmospheric turbulence obtained in task 4 was compared with experimental data on sound scattering into a refractive shadow zone measured by M. Galindo and D. Havelock [Proc. 7th Int. Symp. on Long Range Sound Propagation, Ecully, France 149-159 (1996)]. This comparison is shown in figure 3. It follows from the figure that the agreement between theory and experiment is quite good.

Task 6 To find an optimum separation between microphones in direction-finding arrays and to develop new schemes of such arrays based on principles of acoustic tomography. This task is important for improvement of performance of direction-finding arrays.
Accomplishment:
This task was completed in references [1,9,12,15,16,27]. First, an optimum separation between microphones in direction-finding arrays was calculated in references [12,16] using inhomogeneous von Karman spectra of temperature and velocity fluctuations. Secondly, a new scheme for source localization in the atmosphere by means of acoustic tomography was proposed and studied in detail [9,15,27]. This scheme is intended for localization of aircraft, helicopters, and missiles, and accounts for sound refraction due to atmospheric stratification. In this scheme, the vertical profiles of temperature and wind velocity can also be restored. The proposed scheme is based on ray theories of sound propagation in a stratified moving atmosphere. The ray theories, known in the literature, were compared in reference [1] in detail and the correct theories were distinguished from the incorrect ones.

Task 7 To develop theories of acoustic remote sensing of a stratified moving atmosphere using sodars and to study the effects of atmospheric stratification on this remote sensing. Sodars are widely used (including ARL) for acoustic remote sensing of the wind velocity vector $\mathbf{v}$, and the structure parameters C_T^2 and C_v^2. However, in such remote sensing, the effects

of atmospheric stratification are usually ignored. The goal of this task was to study these effects. The results obtained in this task can be used for improvement of performance of sodars.

Accomplishment:

Theories of acoustic remote sensing of a stratified moving atmosphere with arbitrary vertical profiles of temperature and wind velocity were developed in references [2,7,8,21]. First, the effects of the vertical profiles of temperature and wind velocity on remote sensing of C_T^2 and C_v^2 in bistatic scheme of acoustic sounding were studied [8]. Secondly, a monostatic scheme of acoustic sounding of a stratified moving atmosphere was studied in detail [7,21]. It was shown that, for moderate to strong wind, C_v^2 can significantly contribute to the signal measured by a monostatic sodar. Therefore, in these cases, it is invalid to interpret the scattered signal measured by a monostatic sodar as solely dependent upon C_T^2, even though this interpretation has been commonly used in practice. Third, the effects of atmospheric stratification on remote sensing of wind velocity vector were studied [2]. It was shown that these effects can be significant and can be easily taken into account by algorithms developed.

3 LIST OF ALL PUBLICATIONS UNDER SPONSORSHIP OF THIS GRANT:

- **Papers published in peer-reviewed journals**

1 V. E. Ostashev, D. Hohenwarter, K. Attenborough, Ph. Blanc-Benon, D. Juvé, and G. H. Goedecke, "On the refraction law for a sound ray in a moving medium," *Acustica-acta acustica* **87**, No 3, 303-306 (2001).

2 V. E. Ostashev, T. M. Georges, S. F. Clifford, and G. H. Goedecke, "Acoustic sounding of wind velocity profiles in a stratified moving atmosphere," *J. Acoust. Soc. Am.* **109** 2682-2692 (2001).

3 E. Salomons, V. E. Ostashev, S. Clifford and R. Lataitis, "Sound propagation in a turbulent atmosphere near the ground: An approach based on the spectral representation of refractive index fluctuations," *J. Acoust. Soc. Am.* **109** 1881-1893 (2001).

4 V. E. Ostashev, E. Salomons, S. Clifford, R. Lataitis, D.K. Wilson, Ph. Blanc-Benon, and D. Juvé, "Sound propagation in a turbulent atmosphere near the ground: A Parabolic equation approach," *J. Acoust. Soc. Am.* **109** 1894-1908 (2001).

5 D. K. Wilson, and Ostashev V.E., "Statistical moments of the sound field propagating in a random, refractive medium near an impedance boundary", *J. Acoust. Soc. Am.* **109** 1909-1922 (2001).

6 G. H. Goedecke, R. C. Wood, H. J. Auvermann, V. E. Ostashev, D. Havelock, and C. Ting, "Spectral broadening of sound scattered by advecting atmospheric turbulence," *J. Acoust. Soc. Am.* **109** 1923-1934 (2001).

7 V. E. Ostashev and D. K. Wilson, "Relative contributions from temperature and wind velocity fluctuations to the statistical moments of a sound field in a turbulent atmosphere," *Acustica-acta acustica* **86**, No 2, 260-268 (2000).

8 V. E. Ostashev, G. H. Goedecke, R. Wood, H. Auvermann, and S.F. Clifford, "Sound scattering cross section in a stratified moving atmosphere," *J. Acoust. Soc. Am.* **105**, No 6, 3115-3125 (1999).

- **Papers published in conference proceedings**

9 D. K. Wilson, A. Ziemann, and V. E. Ostashev, "An overview of acoustic travel-time tomography in the atmosphere and its potential applications," Int. Workshop: Tomography and Acoustics: Recent developments and methods, 94 - 101, Leipzig, (2001).

10 V. E. Ostashev, and D. K. Wilson, "Line-of-sight sound propagation through anisotropic and inhomogeneous atmospheric turbulence," Int. Workshop: Tomography and Acoustics: Recent developments and methods, 63 - 70, Leipzig, 2001.

11 V. E. Ostashev, S. F. Clifford, R. J. Lataitis, Ph. Blanc-Benon, and D. Juve, "The effects of atmospheric turbulence on the interference of the direct and ground reflected waves," Proc. 29th Inter. Congr. Noise Control Engineering, Nice, France (2000).

12 D. K. Wilson, V. E. Ostashev, and A. Voronovich, "Source localization in the atmosphere by means of beamforming and tomography," Proc. 29th Inter. Congr. Noise Control Engineering, Nice, France (2000).

13 V. E. Ostashev and D. K. Wilson, "Closed equations for statistical moments of a sound field in a turbulent, refractive atmosphere near an impedance ground and their solutions," Proc. 29th Inter. Congr. Noise Control Engineering, Nice, France (2000).

14 Ph. Blanc-Benon, J. Wasier, D. Juvé and V. E. Ostashev, "Experimental studies of sound propagation through thermal turbulence near a boundary," Proc. 29th Inter. Congr. Noise Control Engineering, Nice, France (2000).

15 V. E. Ostashev, A. Voronovich, and D. K. Wilson, "Acoustic tomography of the atmosphere," IGARSS 2000, Honolulu, U.S.A., 1186-1188 (2000).

16 D. K. Wilson and V. E. Ostashev, "A reexamination of acoustic scattering in the atmosphere using improved models for the turbulence spectrum," Proceedings of the Battlespace Atmospheric and Cloud Impacts on Military Operations Conference 2000," Ft. Collins, CO (2000).

- **Papers presented at meetings**

17 V. E. Ostashev and D. K. Wilson, "The effects of turbulence anisotropy and inhomogeneity on line-of-sight sound propagation," *J. Acoust. Soc. Am.* **109**, No 5, Pt.2, 2406 (2001).

18 D. K. Wilson and V.E. Ostashev, "Numerical solution of a second-moment parabolic equation for sound propagation in a random medium," *J. Acoust. Soc. Am.* **106**, No 4, Pt.2, 2145 (1999).

19 V. E. Ostashev, J. Wasier, Ph. Blanc-Benon, and D. Juvé, "Propagation of a monochromatic sound wave in a turbulent atmosphere near the ground: Theory and laboratory experiment," *J. Acoust. Soc. Am.* **106**, No 4, Pt.2, 2144-2145 (1999).

20 G. H. Goedecke, R. C. Wood, H. J. Auvermann, and Ostashev V.E., "Spectral broadening of sound scattered by atmospheric turbulence," *J. Acoust. Soc. Am.* **106**, No 4, Pt.2, 2145 (1999).

21 V. E. Ostashev and D. K. Wilson, "The effects of the wind velocity fluctuations on the sound backscattering cross-section in the stratified moving atmosphere," *J. Acoust. Soc. Am.* **106**, No 4, Pt.2, 2145 (1999).

22 V. E. Ostashev, G. H. Goedecke, and R. C. Wood, "Scattering of sound in a stratified moving atmosphere," *J. Acoust. Soc. Am.* **105**, No 2 (Part 2), 1338 (1999); *Acustica-acta acustica* **85**, Suppl. 1, S 412 (1999).

23 V. E. Ostashev and G.H. Goedecke, "Sound propagation near the ground in a turbulent atmosphere," *J. Acoust. Soc. Am.* **105**, No 2 (Part 2), 1387 (1999); *Acustica-acta acustica* **85**, Suppl. 1, S 461 (1999).

- **Papers in press or in preparation**

24 V. E. Ostashev, D. K. Wilson, and G. H. Goedecke, "Sound propagation and scattering through inhomogeneous, anisotropic atmospheric turbulence," BACIMO 2001 (in press).

25 G. H. Goedecke, S. Moore, H. J. Auvermann, and V. E. Ostashev, "Quasi-wavelet model of anisotropic inhomogeneous atmospheric turbulence," BACIMO 2001 (in press).

26 V. E. Ostashev, D. K. Wilson "Log-amplitude and phase fluctuations of a plane wave propagating through anisotropic, inhomogeneous turbulence," *Acustica-acta acustica* (in press).

27 D. K. Wilson, A. Ziemann, V. E. Ostashev, and A. G. Voronovich, "An overview of acoustic travel-time tomography in the atmosphere and its potential applications," *Acustica-acta acustica* (in press)

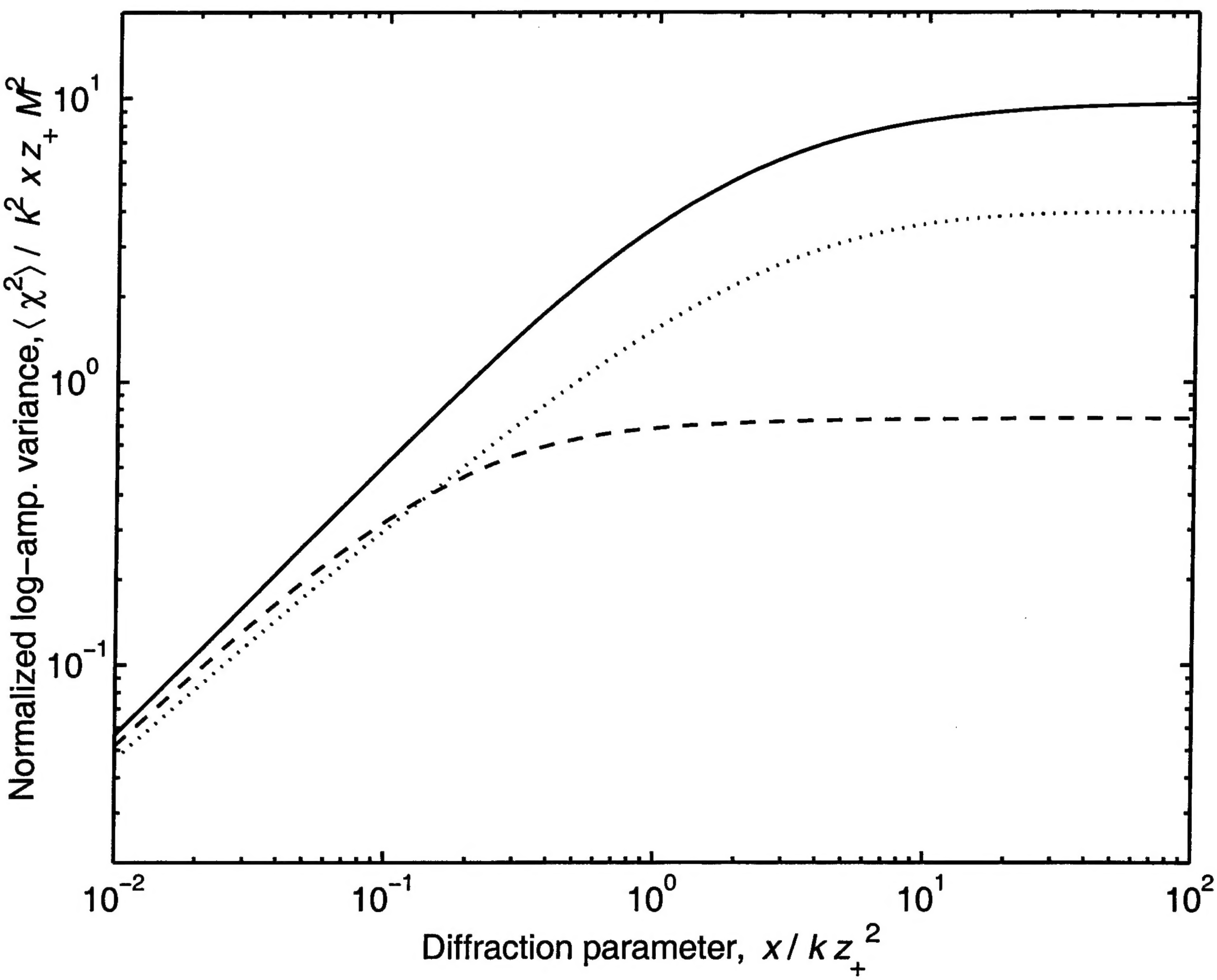
28 V. E. Ostashev, D. K. Wilson "The effects of turbulence intermittency on line-of-sight sound propagation through a turbulent atmosphere," *J. Acoust. Soc. Am.* (in preparation).

4 LIST OF PARTICIPATING SCIENTIFIC PERSONAL

1. Dr. Vladimir E. Ostashev.
2. Dr. George H. Goedecke.
3. Graduate student Roy C. Wood. Degree earned: Ph.D. in Physics, NMSU, May, 1999.
4. Graduate student Stephen Moore.

5 REPORT OF INVENTIONS

None



Normalized log–amp. variance, $\langle\chi^2\rangle$ / $k^2\,x\,z_+\,M^2$
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
10^2
Diffraction parameter, $x\,/\,k\,z_+^{\;2}$

Figure 1

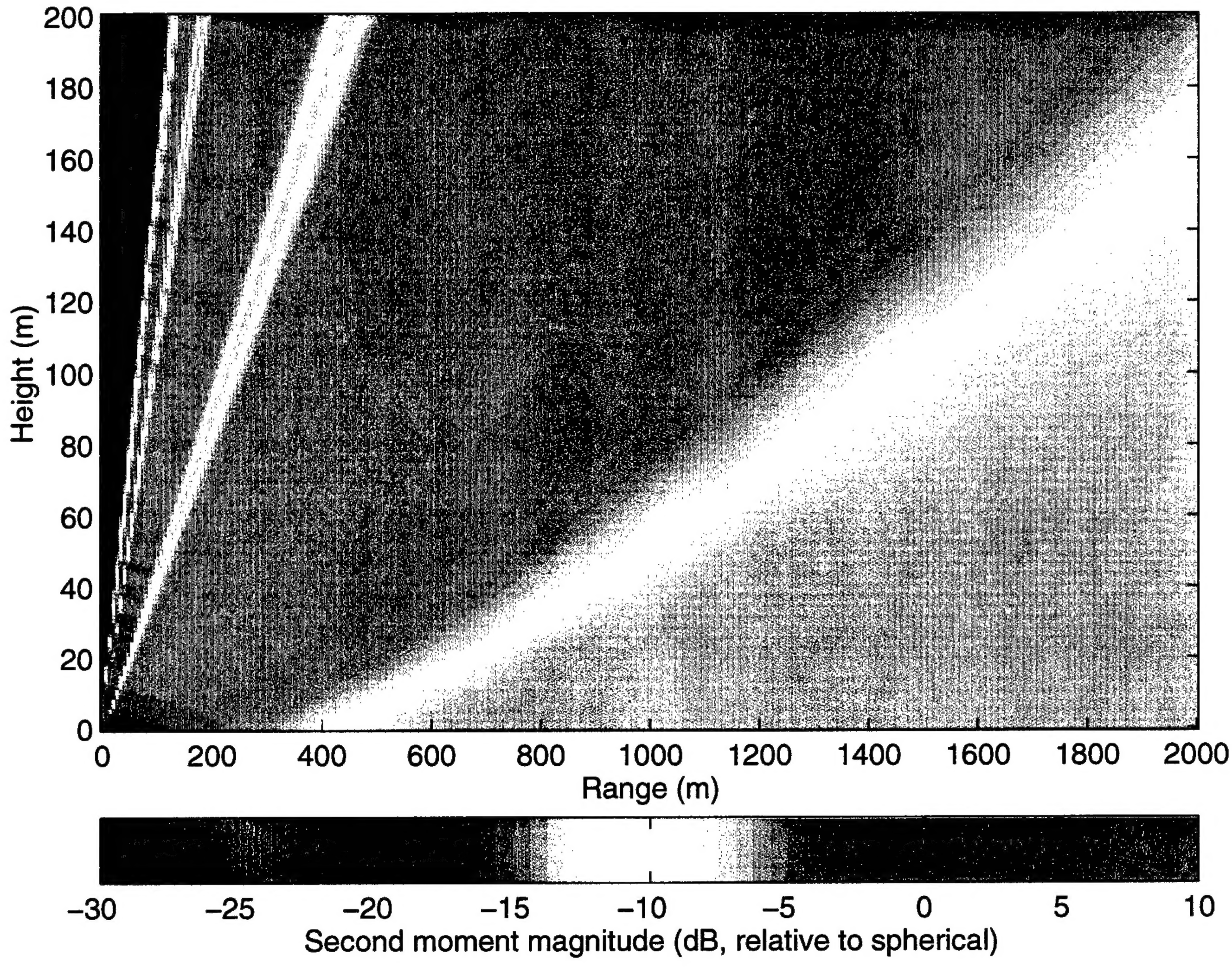

200
180
160
140
120
100
80
60
40
20
0
Height (m)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Range (m)
-30
-25
-20
-15
-10
-5
0
5
10
Second moment magnitude (dB, relative to spherical)

Figure 2

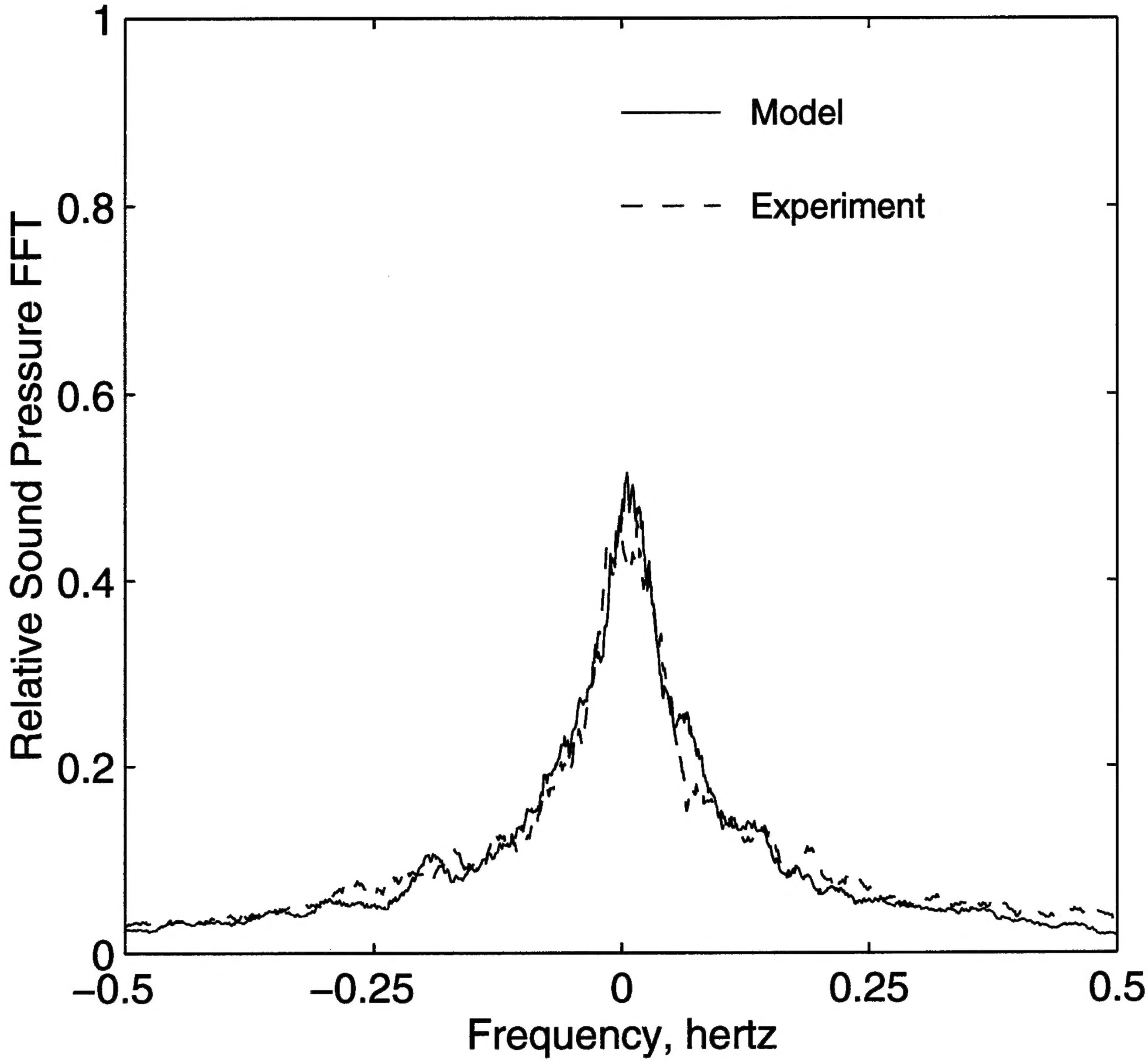

Model
Experiment
Relative Sound Pressure FFT
Frequency, hertz
1
0.8
0.6
0.4
0.2
0
−0.5
−0.25
0
0.25
0.5

Figure 3